The wet and stormy UK winter of 2019/2020

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Introduction

The winter of 2019/2020 was remarkable on many fronts. The United Kingdom experienced its wettest February on record for the UK overall, England, Wales and Northern Ireland, and second wettest for Scotland in series from 1862, and one of the four named windstorms affecting the UK, *Dennis*, was one of the deepest Atlantic depressions on record.

The weather pattern during the winter was primarily the result of a strongly positive North Atlantic Oscillation (NAO). The associated strong north–south surface pressure gradient across the North Atlantic and westerly regime brought a succession of cyclonic systems, persistent heavy rain and associated severe floods to much of the UK. During February, when the UK experienced a peak in rainfall extremes, three named windstorms *Ciara* (8/9 February), *Dennis* (15/16 February), and *Jorge* (28/29 February) accounted for approximately 44% of the February rainfall total.

Met Office long range forecasts successfully predicted a strongly positive NAO and extratropical wave trains in the forecast circulation emanating from tropical latitudes. This allowed the Met Office to warn UK contingency planners of an increased risk from heavy rainfall and storms.

Climate change has also increased the probability of daily and multi-day rainfall extremes for the UK. Our analysis suggests that climate variability was the primary factor driving this event. However, as a consequence of increased greenhouse gas concentrations and the resulting global climate change, extreme rainfall like that in February 2020 is now more likely in the current climate and expected to increase further by 2100.

Winter 2019/2020 and its historical context

Winter 2019/2020 covers the period December 2019 to February 2020 inclusive. This period followed a wet summer and autumn with a number of notable flooding events across parts of the UK (see Sefton C, Muchan K, Parry S *et al.*, submitted to *Weather*, for more detail). In particular, Wainfleet in Lincolnshire saw 156mm during 10–12 June, and intense downpours caused flash flooding across northern England on 30/31 July contributing to the Toddbrook reservoir overtopping and the potential failure of the dam. Autumn 2019 was one of the wettest on record for many catchments and communities in northern England with floods continuing to affect Wales, central England and northern England.

Some of the most significant rainfall and flooding took place during 7–10 November across South Yorkshire and the East Midlands (Met Office, 2019) with impacts lasting for 10 days at Fishlake, South Yorkshire. By the end of November, soils were wetter than average for the time of year across nearly all of England (Environment Agency (EA), 2019).

For the rest of the winter, a succession of low pressure systems crossed the UK. Figure 1 shows UK daily rainfall totals during winter 2019/2020, which highlights the particularly extreme peaks of rainfall associated with named storms *Ciara*, *Dennis* and *Jorge*. Storm *Dennis* became one of the deepest Atlantic depressions on record, with a minimum analysed central pressure of 922hPa at 1800 UTC on 15 February, south of Iceland (Figure 2).

The UK average daily rainfall of 27mm on 15 February 2020 is the third highest UK daily rainfall total in a Met Office series from 1891[1] derived from HadUK-Grid (Hollis *et al.*, 2019). It was surpassed only by 30mm on 25 August 1986 at that time, and then subsequently by a provisional value of 32mm in October 2020 (Kendon and McCarthy, 2021), highlighting the widespread and extreme nature of the rainfall associated with that weather system. In the HadUK-Grid daily rainfall series (Hollis *et al.*, 2019) only 40 days since 1891 (less than 0.1% of all days) have a UK daily rainfall in excess of 20mm. Both *Ciara* and

[1]This would be equivalent to *c.* 6.5km^3 of water falling on the UK that day. Volume of Loch Ness is *c.* 7.5km^3

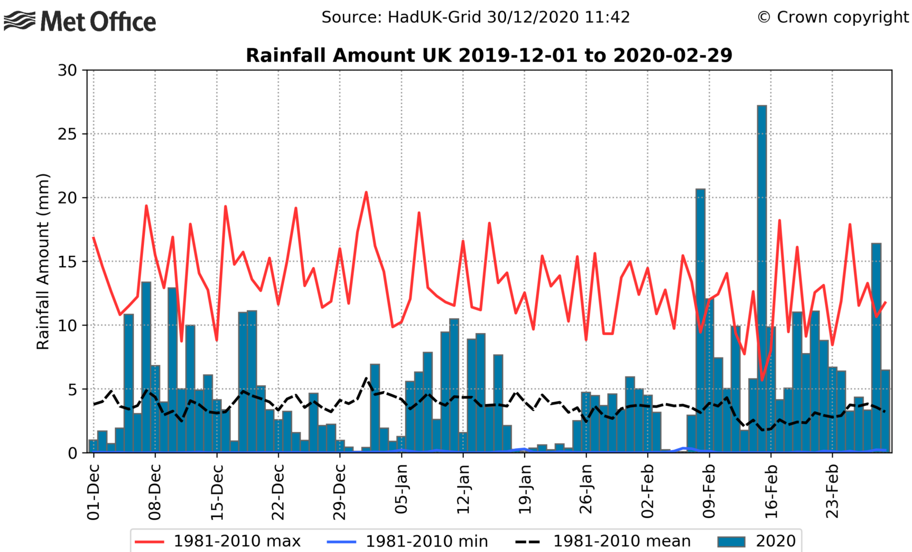

Figure 1. UK rainfall for winter 2019/2020. Daily rainfall area averaged over the UK for each day through winter 2019/2020 from HadUK-Grid (Hollis et al., 2019).

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Dennis exceeded this threshold. Having two such widespread extreme rainfall events in the same calendar month is very rare and suggests a systematic forcing of conditions in that month. Storms *Ciara* and *Dennis* alone account for just over 37% of the total rainfall during February 2020, and with Storm *Jorge* at the end of February account for 44%. The facts and figures of the flood events that occurred between June 2019 and February 2020 are also reported by Sefton C, Muchan K, Parry S *et al.* (submitted to *Weather*).

February 2020 – an exceptionally wet month

February 2020 was the wettest February on record for the UK overall, England, Wales and Northern Ireland, and second wettest for Scotland in series from 1862. It was also the fifth wettest calendar month for all months. It was also a notably mild February, particularly for southern England, and one of the top 10 warmest for England and Wales overall.

The highest areal-average rainfall anomaly for any county was West Yorkshire, which provisionally recorded 236mm, the wettest February in a series from 1862 by a margin of over 50mm (see Figure 3) and 359% of the 1981–2010 February long-term average. At county level, rainfall anomalies of over 300% are extremely unusual and West Yorkshire at 359% lies in the 1/10 000 extreme tail of the monthly distribution as shown in Figure 4.

The North Atlantic Oscillation

The NAO was predominantly positive during winter 2019/2020, meaning that the north–south pressure gradient across the North Atlantic between the 'Icelandic Low' and the 'Azores High' was stronger than normal, putting the UK in a strong westerly flow regime. The upper-level jet stream was also much stronger than usual and directed the North Atlantic storm track towards the UK and northern Europe.

Both of these situations are summarised for February 2020 in Figure 5, showing the UK sitting under a strong north to south pressure gradient and the resultant zonal jet stream. A positive NAO during winter is usually associated with wetter than normal conditions across northern Europe and drier than average conditions for southern Europe and the Mediterranean region (Scaife *et al.*, 2008) which is what the reanalysis in Figure 5 shows for February 2020.

We can quantify the relative contribution of the atmospheric circulation and long-term trends to the winter rainfall using methods outlined in O'Reilly *et al.* (2017) and McCarthy *et al.* (2019). For each day of winter 2019/2020, we identified historical

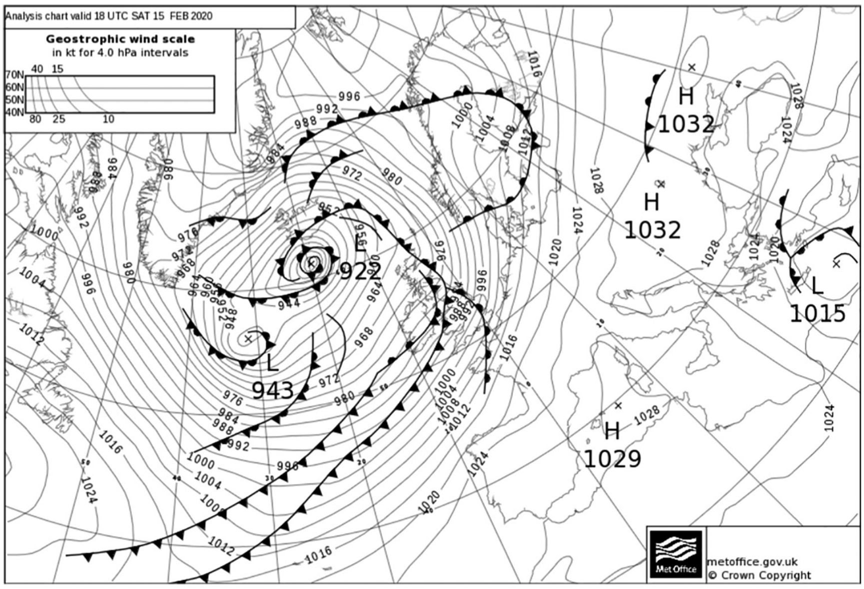

Figure 2. Met Office synoptic analysis showing Storm Dennis (1800 UTC, 15 February 2020) at its lowest analysed pressure of 922hPa.

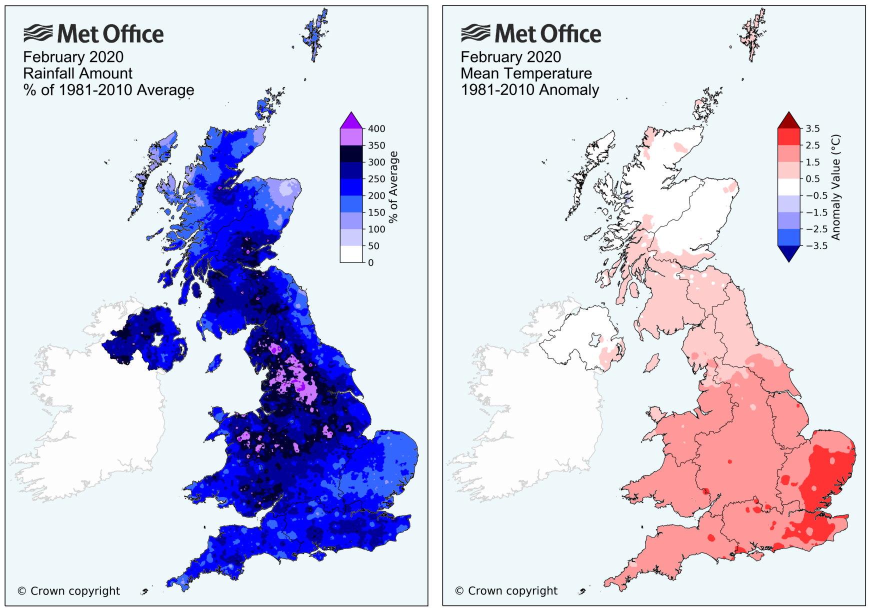

Figure 3. Rainfall and temperature anomaly maps for February 2020 relative to the 1981–2010 average. Most of the UK received over 200% of average rainfall, with fairly extensive areas exceeding 300% and locally over 400%.

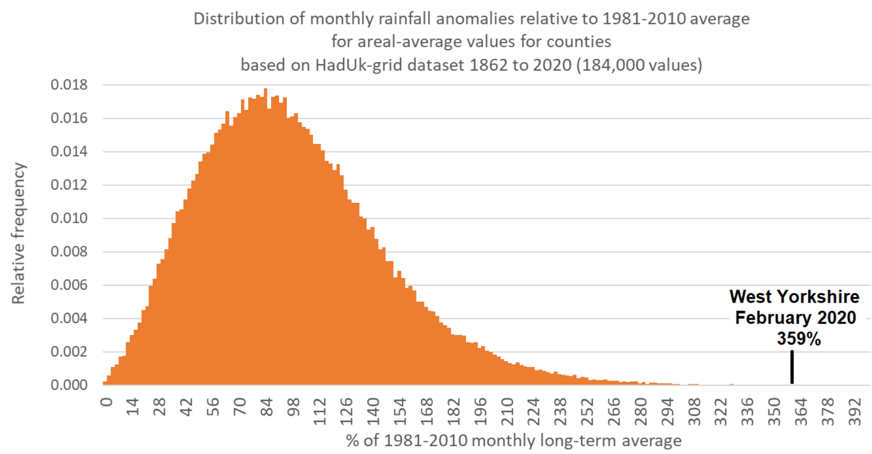

Figure 4. Distribution of areal-average UK monthly rainfall anomalies for all counties (97) and all months (12) and all years (159) from the HadUK-grid dataset of monthly gridded rainfall data extending back to 1862.

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analogue days (i.e. days in the same month of previous years with the closest UK-region atmospheric circulation). Each day's rainfall was then reconstructed as a weighted combination of the rainfall from its analogue days. The circulation based reconstruction is therefore an estimate of how much of the rainfall during winter 2019/2020 can be associated with the observed atmospheric circulation. Figure 6 shows that the circulation anomaly accounts for the majority of the observed rainfall anomaly. A smaller component due to the trend is also apparent.

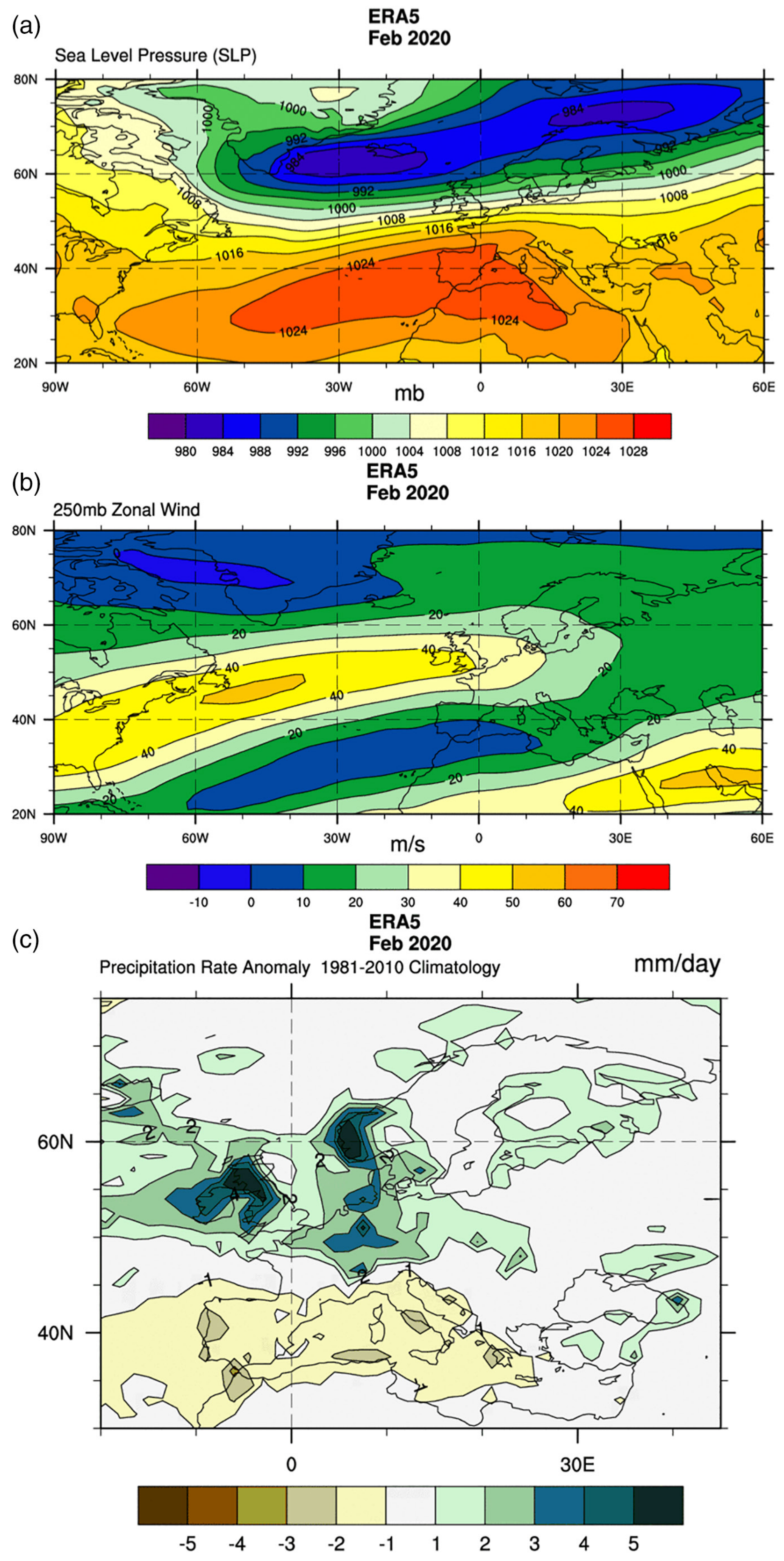

Figure 5. The meteorology of February 2020. (a) Mean sea level pressure for February 2020 across the North Atlantic and Europe Sector. (b) 250hPa zonal wind speed. (c) Rainfall anomalies across Europe for February 2020. Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at https://www.esrl.noaa.gov/psd/ and generated from ERA5 reanalysis (Hersbach et al., 2020).

How predictable was the winter of 2019/2020?

Strong predictable signals were found in seasonal forecasts for the 2019/2020 winter mean (December–February) initialised well before the start of winter. Figure 7 shows the sea level pressure anomaly from the Met Office GloSea5 system (MacLachlan *et al.*, 2015) for forecasts initialised in early November. A clear signal for lower than normal pressure over the Arctic and higher than normal pressure in the Aleutian and Azores regions indicated a likely positive phase of the NAO and Arctic Oscillation (AO)[2] during this winter.

Similar signals were seen in model runs initialised at earlier and later dates and also in other forecast systems (not shown). The NAO and AO are skilfully predicted by GloSea5 (Scaife *et al.*, 2014; MacLachlan *et al.*, 2015) and these extratropical forecast signals can often be explained by tropical rainfall variability which creates predictable extratropical wave trains in the forecast circulation (Scaife *et al.*, 2017, 2019).

Winter 2019/2020 was a clear example where large tropical rainfall anomalies were predicted. Despite weakly positive El Niño-Southern Oscillation (ENSO) sea surface

[2]The Arctic Oscillation is a climate index relating to the state of the atmospheric circulation over the Arctic and closely related to the NAO.

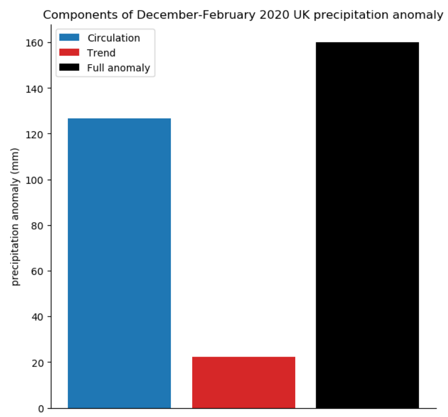

Figure 6. Components of the total December, January and February 2019/2020 UK precipitation anomaly. The total anomaly (black bar) contains components due to circulation (blue bar) estimated using daily reanalysis MSLP fields, and the long-term trend (red bar). The trend component is 22mm – this equates to a trend of 0.17mm year^{-1} over the 1891/1892 to 2019/2020 period for which daily data are available.

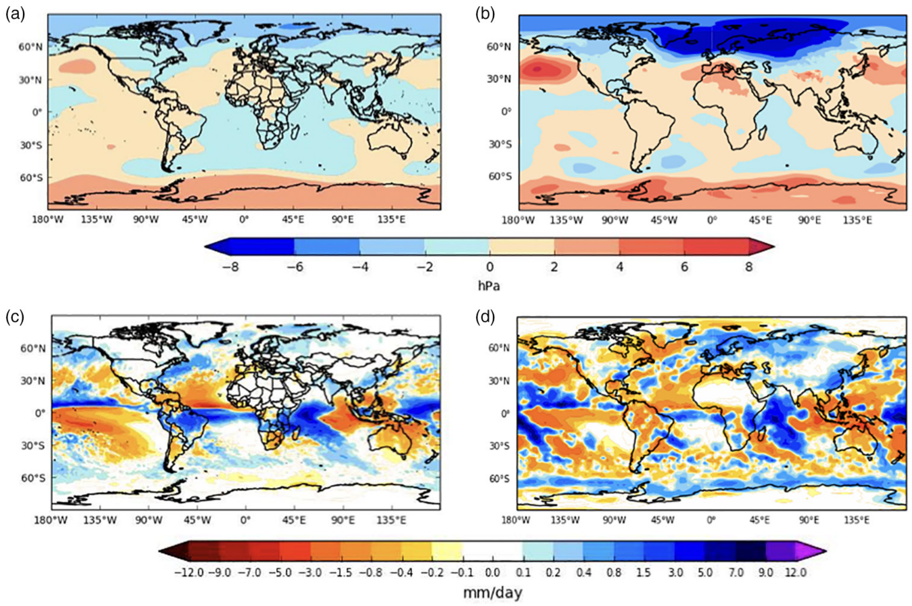

Figure 7. Seasonal forecast for winter 2019/2020. (a) Forecast MSLP anomaly (hPa) from GloSea5, using 21 start dates in November 2019. (b) MSLP anomaly (hPa) in observational analysis relative to the same 1993–2016 climatology. (c) Ensemble mean forecast precipitation anomaly (mm day^{-1}). (d). Observed December-to-February precipitation anomaly (mm day^{-1}) with respect to the 1981–2010 climatology, using data from the Global Precipitation Climatology Project (GPCP) version 2.3 combined dataset (Adler et al., 2003).

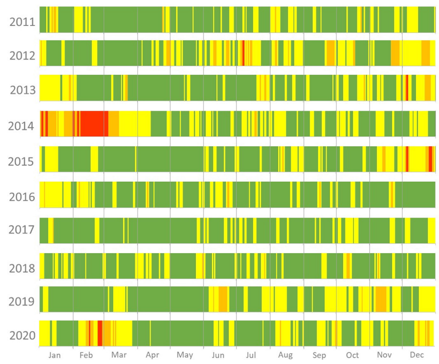

Figure 8. Flood Forecasting Centre activity coutesy of Rob Cowling. Shown is the flood guidance statement 'Operational Activity' calendar from 2011 to 2020. The colours reflect the level of the forecast flood risk (based on impact level and likelihood). Green is the lowest level, rising through yellow and orange with red being the highest flood risk category, for example, winter 2013/2014 and December 2015.

temperature (SST) anomalies, the winter was predicted to have a La Niña-like rainfall state with weak rainfall in the central and eastern tropical Pacific, while the Indian Ocean exhibited a very strong positive phase of the Indian Ocean Dipole (Saji and Yamagata, 2003) with increased rainfall in the western Indian Ocean and decreased rainfall in the eastern Indian Ocean (Figure 7(c)). Consistent with this signal and the delayed effect via the strengthened stratospheric polar vortex, the forecast ensemble mean presented low pressure over the Arctic and a very strongly positive NAO (Hardiman *et al*., 2020) and AO (Figure 7(a)), similar to the observed pressure pattern (Figure 7(b)) with a low pressure anomaly across the Arctic and a high pressure anomaly over the southern North Atlantic.

The winter NAO anomaly of around +15hPa in 2019/2020 was close to 2 standard deviations above normal. Note that while the forecast anomaly closely resembles the observed pattern it is considerably weaker in amplitude. While this is expected from ensemble averaging and reduction of unpredictable noise in creating the ensemble mean, the forecast ensemble signals are also known to be 2–3 times too weak in amplitude (Eade *et al*., 2014), hence our focus on the ensemble mean. The clear signals in this winter forecast meant that long-range outlooks for the winter season were able to warn UK contingency planners of increased risk from heavy rainfall and storms. The winter three month outlook, issued in November, warned that upper quintile winter rainfall was twice as likely as lower quintile rainfall and warned of an increased likelihood of impacts from high winds and heavy rainfall compared to what is normally expected at this time of year.

Present-day risk of extreme rainfall – the UNSEEN method

The UK has experienced other, regional, record monthly winter rainfall extremes in the last decade. Of particular note were the winters of 2013/2014 (in southeast England; Kendon and McCarthy, 2015) and December 2015 (in northwest England and southern Scotland; McCarthy *et al*., 2016). These events led to widespread flooding impacts in these regions, which can be seen in the incidence of the highest flood risk level of the Flood Forecasting Centre shown in Figure 8.

In the wake of these successive costly flooding events, the UK government commissioned a National Flood Resilience Review (NFRR[3]) with the stated aim of establishing a 'worst-case scenario' for winter UK flooding in the current climate. As part of this work, the Met Office developed a new methodology, UNprecedented Simulated Extremes using ENsembles (UNSEEN, Thompson *et al*., 2017), that uses climate model simulations to quantify the chance of extreme events. UNSEEN utilises large model ensembles of coupled climate simulations (~60km atmospheric resolution) from near-term prediction studies (Dunstone *et al*., 2016). At ~60km resolution the model cannot simulate the orographic enhancement seen in some areas, such as the Highlands of Scotland. However, the model monthly winter rainfall simulation over most regions in England is statistically indistinguishable from that observed (Thompson *et al*., 2017).

These ensembles provide approximately two orders of magnitude more simulations of the current climate than is available from modern historical records and are therefore able to simulate a wider range of plausible extreme events. Focusing on southeast England, the UNSEEN method estimates a 7% chance of unprecedented rainfall in at least one month in any given winter (October–March). Expanding the analysis to other regions in England and Wales, the risk increases to a 34% chance of breaking a regional monthly record somewhere each winter in the current climate (Thompson *et al*., 2017).

Are UK winters getting wetter?

For the most recent decade (2010–2019) winters have been 5% wetter than the 1981–2010 average and 12% wetter than the 1961–1990 average (Kendon *et al*., 2020). Of the top ten wettest winters, four have occurred since 2007 and seven since 1990 (Figure 9). Associated with these changes we have also observed a 17% increase in the total rainfall from extremely wet days,[4] whilst Kendon (2014) showed the 2010s contain more monthly to seasonal UK rainfall records than any other decade in the observational record. It is also notable that three of the five wettest calendar months on record have occurred since 2009, the wettest months being October 1903 (227mm), December 2015 (217mm), November 2009 (215mm), December 1929 (213mm), and

[3]https://www.gov.uk/government/publications/national-flood-resilience-review

[4]https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/state-of-uk-climate/soc_supplement-002.pdf

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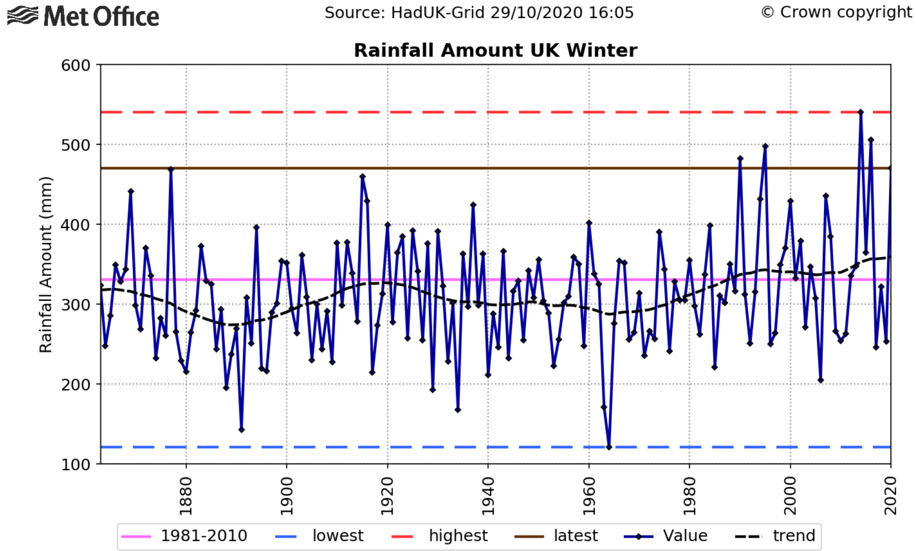

Figure 9. Winter rainfall for the UK 1862–2020. The solid brown line indicates the total for 2019/2020.

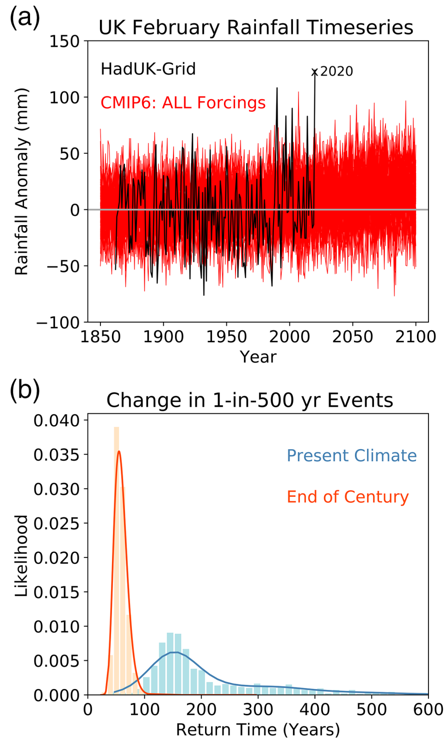

Figure 10. Attribution of extreme February rainfall to anthropogenic forcing. (a) Timeseries of the UK February mean rainfall (shown as anomalies relative to 1901–1930) from the ALL model simulations (red) and the observation (black). The 2020 anomaly is marked by the cross. (b) Normalised distributions of the return time of extremely wet Februarys in the UK in the present climate (blue) and the climate of the late 21st century (orange). Extreme events are months with more rainfall than a 1-in-500-year event in the natural climate.

February 2020 (209mm). However, rainfall changes are regionally dependent with the most marked increases for both mean and extreme rainfall being across western Scotland and very little or no apparent change for southern England (Kendon *et al.*, 2020). Figure 9 also highlights the large inter-annual and decadal variability in UK winter rainfall that can make robust detection of long term trends in UK rainfall challenging.

A cluster of very significant daily, monthly and seasonal rainfall extremes have occurred in the most recent decade including the extreme wet winters of 2013/2014 and 2015/2016. The latter included Storm *Desmond* that recorded the highest 24 hour rainfall total on record for the UK: 341.4mm on 5 December 2015 at Honister Pass (Cumbria). Several more localised records have also been set with several counties including South Yorkshire, Nottinghamshire and Lincolnshire having their wettest autumn on record in 2019.

Attribution to climate change

Attribution of weather and climate extremes estimates in a quantitative manner how human influence on the climate may alter characteristics of extreme events, such as their likelihood or magnitude (Stott *et al.*, 2016). Unlike natural variability which may only lead to short-term climatic changes, human influence (for example, from increasing greenhouse gas emissions) may lead to long-term climatic shifts. Here we follow the well-established risk-based approach, whereby the likelihood of an event is derived from distributions of the relevant meteorological variable in the real world, as well as in a 'natural' world without the effect of human influence on the climate (Christidis *et al.*, 2018). The change in the risk due to anthropogenic forcings is then estimated by comparing the probabilities of the event in these two types of climate. The questions we set out to answer are: '*how has the likelihood of an extremely wet February in the UK changed relative to the natural climate?*' and '*how much more will it change by the end of the century?*' It should be noted that the attribution assessment defines an extreme event as the exceedance of a high rainfall threshold in any given winter in the current climate, independently of other drivers such as the atmospheric circulation anomalies described above that also played an important role in the wet February of 2020.

A suite of nine state-of-the-art climate models that participated in the Coupled Model Inter-comparison Project 6 (CMIP6; Eyring *et al.*, 2016) is used in this analysis. The models provide 51 simulations of the real world with all forcings acting on the climate (ALL) and 54 simulations of the natural world (NAT) without anthropogenic forcings. The ALL simulations were extended to the end of the 21st century with the SSP2-4.5 scenario (O'Neill *et al.*, 2016). The Shared Socioeconomic Pathways (SSPs) offer a range of 'pathways' that describe how socioeconomic factors such as population, economics and technology might change over this century in the absence of climate policy, but under different levels of climate change mitigation. SSP2-4.5 describes a 'middle of the road' pathway.[5] The advantage of using large ensembles in our analysis is that they provide different representations of the climate, which accounts for the effect of climate variability and enables us to detect whether the anthropogenic effect has emerged above it.

The February rainfall over the total UK land area is computed for all the simulated years. Rainfall anomaly time-series from the ALL simulations are illustrated in Figure 10(a) together with observed time-series from the HadUK-Grid observational dataset. The observed anomaly in the year 2020 stands markedly above all previous years and the model simulations do not match it, even in future decades, when February rainfall is projected to increase. This demonstrates that the volume of rainfall during February 2020 was an exceptional event when compared to historical simulations and projections with CMIP6 models, which appear to underestimate UK February rainfall variability. Since the models do not reproduce anything as high as the observed rainfall, we translate the event into something equivalent in the model world. The observations indicate the event could be as rare as a 500-year event in the natural world, so we look for this threshold in the natural world simulations and use it for the attribution assessment.

The ALL simulations suggest a mean increase in rainfall of 0.38mm per decade, while the NAT simulations give a near-zero trend (–0.002mm per decade). During the observational period (1862–2020) HadUK-Grid yields a positive trend of 0.55mm

[5]https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change

decade⁻¹. The high variability in UK rainfall however means that quantitative trend estimates are very sensitive to the choice of start and end dates.

We also recompute the return time after subtracting an estimate of the anthropogenically forced rainfall response (provided by the mean of the ALL simulations) from the observations to obtain an estimate of about 560 years for the 2020 event in a natural climate. These estimates have large uncertainties due to sampling limitations and should only be viewed as rough indications. In our attribution analysis, we estimate the 1-in-500-year event using all the Februarys extracted from NAT simulations and use it as a threshold to define extremes in the models that are at least as intense as in 2020. We extract Februarys from the ALL simulations (a) in years 2005–2034 to represent the present-day climate, and (b) in years 2071–2100 for the late 21st-century climate and calculate the probability of the total monthly rainfall being above the selected threshold. As in previous work, extreme probabilities are estimated with the Generalised Pareto Distribution (GPD) and the associated uncertainty with a Monte Carlo bootstrapping procedure (Christidis *et al*., 2013).

Return times (inverse probabilities) of extreme events are illustrated in Figure 10(b). The models suggest that 500-year events now have a return time of 169 years, which may be further reduced to 56 years by the end of the century. There is large uncertainty in both of these estimates, ranging from about 100 years to infinity. Extreme events like February 2020 may have thus now become about 3 times more likely and the models suggest they may become about 9 times more likely by 2100, although these estimates are uncertain due to limitations in current models' representation of observed rainfall variability. Our results are consistent with previous work that showed increases in the likelihood of extreme winter rainfall in the UK due to anthropogenic influence on the climate (Christidis and Stott, 2015).

Changing risk of extremely wet UK events

Attribution analysis can quantify potential changes in the risk of extremes, but the high variability of UK rainfall means that trends in regional rainfall at the scale of the UK resulting directly from anthropogenic climate change are not expected to be detectable in the observational record at present (Sarojini *et al*., 2016). This is also the case for shorter duration extremes (Kendon *et al*., 2018).

Probabilistic projections from the latest set of UK Climate Projections (UKCP18, Murphy *et al*., 2018) give a central estimate of change in February precipitation by the 2080s for a high emissions scenario (RCP8.5) as 13% (with a 5th–95th percentile range of –13% to 49%), and for a low emissions scenario (RCP2.6) of 6% (with a range of –18% to 27%). The UKCP18 Global Projections (also called 'strand 2' in Murphy *et al*., 2018) can be used to supplement the probabilistic projections. These consist of an ensemble of 15 perturbed parameter model variants (PPE-15) and a set of 13 models from the Coupled Model Intercomparison Phase 5 (CMIP5-13). Figure 11 compares time series of UK February precipitation from 1900–2100 from observations (HadUK-Grid, black) with those from PPE_15 (blue) and CMIP5_13 (orange).

For the historical period (1900–2020) the climate simulations tend to underestimate the magnitude of inter-annual variability with a standard deviation around two-thirds of the observed value. It is noticeable that February 2020 (137% relative to 1981–2010) and February 1990 (119%), both sit outside the spread of the models for the 20th or early 21st century climate. The ensemble averages give increases by the 2080s of 17% (PPE-15) and 11% (CMIP5-13). The global projections also show that there is an increasing likelihood of the level of rainfall seen in February in 1990 and 2020, but not until the second half of the 21st century, which is consistent with the attribution analysis described previously. Furthermore, pooling all models into 50 year blocks (a boxplot of which is shown in Figure 12) shows that wet extremes increase more than the mean, and dry extremes do not change much, resulting in a wider range of variability in the future projections.

In all these studies the use of climate models is essential to quantify these probabilities which would not be possible from the observations alone. For event attribution of the role of climate change, the quantitative estimates are very specific to the event studied. However, these studies contribute to a growing body of evidence that extreme rainfall is a significant risk factor for the UK and that climate change has increased the likelihood of extreme rainfall events.

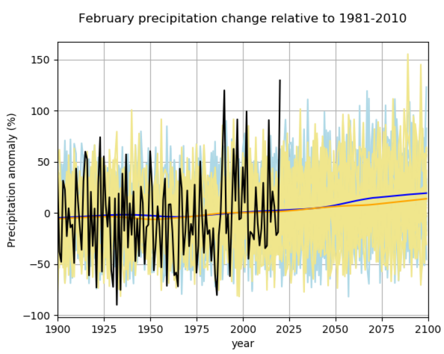

Figure 11. February precipitation anomaly as a percentage of the 1981–2010 average, for observations (black), individual ensemble members of the PPE-15 (light blue), and CMIP5-13 (light orange). The smoothed model ensemble means are shown in dark blue (PPE-15) and orange (CMIP5-13). This is using CMIP5 RCP8.5 scenario, which shows a stronger forcing compared to Figure 12 which is driven from CMIP6 SSP4.5.

Conclusions

The advancement in our knowledge and scientific understanding of weather and climate has led to improved quantification of the current and future likelihood of such extreme events as observed over the UK during winter 2019/2020. Integrating weather and climate observations and information from models across weather and climate time scales has enabled us to provide a more comprehensive analysis of the risk to the UK and our ability to deliver operational safety-of-life services.

The winter experienced in the UK during 2019/2020 was exceptional, culminating with the wettest February on record. A UK average accumulation of 27mm on 15 February (*Dennis*) is the third highest UK daily rainfall total in a Met Office series from 1891 (more than 47 000 days), while the 21mm on 8 February (*Ciara*) ranked 31st highest in the series. Having two such widespread extreme rainfall events in the same calendar month, roughly one week apart, is very rare. Storms *Ciara* and *Dennis* alone account for just over 37% of the total rainfall during February 2020.

We find that the February 2020 UK rainfall is directly attributable to the concurrent strongly positive phase of the NAO and AO and that the conditions during the winter were primarily due to a predictable global scale wave train emanating from the tropics. This allowed long-lead warning of the increased chance of extremes. Notwithstanding the fact the current climate models underestimate climate rainfall variability, future projections show that the UK is likely to experience warmer, wetter winters. Being able to evaluate the changing likelihood of such extreme events is

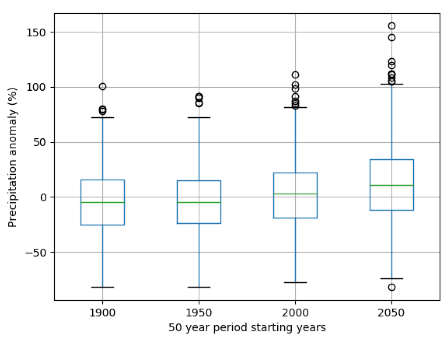

Figure 12. A boxplot of all February rainfall from climate models pooled into 50 year blocks, showing both an increase in median and year-to-year variability from an increase in variability in the upper half of the distribution.

essential for many sectors that need to manage or plan for present and future exposure to such risk. Having a better understanding of climate change effect on the tropics, their dynamical links to the extratropics and in turn their local amplification should be a priority if we want to better estimate the future risk of events like winter 2019/2020.

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